Module 29/ Topic 16

SHELL FOUNDATIONS

Shell foundations are in general economic alternatives to plain shallow foundations in situations involving heavy superstructural loads to be transmitted to weaker soils. The use of shells in foundations, as in roofs, leads to considerable saving in materials, and in the case of shells with the *straight-line property* and *axisymmetric shells*, this is achieved without much extra input of labour. The resulting economy is substantial in the *developing countries* of the world – many of which are in the Asian region, Africa and Latin America – where materials of construction are scarce and expensive, but labour, comparatively cheap and abundant. This factor alone points to the need for the construction industry in these countries to increasingly *gravitate* towards this technique in the interest of conserving the scarce materials of construction, if not economy itself. An added advantage is the scope they offer for *precasting*, thanks to the conspicuous reduction in weight, which makes even large size shell footing amenable to precasting. This section throws light on the scope and inherent advantages of the use of some select shells in different form of substructures, especially foundations.

16.1 Structural efficiency and economy of shells

The basic difference between a plain structural element like a slab and a non-planar structural element like a shell is that, while the former resists vertical loads, including self weight, in flexure, the same loads induce primarily a *direct, in-plane* or *membrane state of stress* in a shell, which may be tension, compression or shear, but all lying in the plane of the shell. Concrete as a material of construction is *most* efficient in direct *compression*, *least efficient* in *tension*, with the efficiency in bending lying between the two. Thus if a plain roof slab is substituted by a shell, and if the geometry and boundary conditions of the shell are such that the same applied load induces a state of membrane compression, and that too of a low magnitude, better material utilisation results, which in terms of design means a substantial *reduction in thickness*. This reduction in thickness, however, has been achieved at the cost of *extra surface area* needed on account of the curvature of the shell, which means that there is a *net* saving in material provided the saving realised due to reduction in thickness *more than offsets* the extra due to curvature. A structure however takes its final shape only when the materials of construction are combined with labour. Shell, which is a *material-saving technique*, can be highly *labour-intensive* depending upon the intricacy of its geometry. This means that if we combine the aspects of material and labour, there will be *net* economy in respect of the shell only when the saving in cost realised from saving in material *more than offsets* the extra due to labour. This indeed turns out to be reality in respect of those shells, which are characterised by the straight-line property, which makes them *ruled surfaces*, and also axisymmetric shells, both of which are not labour-intensive (Kurian, 2006).

The above situation at any rate indicates that the economy with the shell will be more pronounced in countries where material of construction, such as concrete and steel, are scarce and expensive, but labour, comparatively cheap and abundant. The latter are characteristic features of the economies of *developing countries*, particularly in the *Asian, African* and *Latin American* regions. This makes the concept of shell a natural choice in these countries, unlike in the industrially advanced countries of the West where the relative cost picture between material and labour is normally of the reverse order compared to the above (Kurian, 2006).

Historically, traditional materials of construction such as rubble, stone and brick, not to speak of plain concrete, all of which are strong in compression, but weak in tension, were put in the form of *arches* above wall openings subjecting them essentially to axial compression. With the advent of *reinforced concrete*, around the turn of the 20th century, the arch gave way to the *beam*, with the *steel* taking the *tension* and *concrete* the *compression*, in the resulting flexural state. The shell in essence represents a *reversion* of this scenario, that is, from bending to axial compression, thus holding out a strong message for countries of the above mentioned regions.

16.2 Shells in foundations – The cost aspect

If a roof shell of the type described above is inverted and put on soil, we have a shell foundation, and if the load on the shell, which is the soil reaction in this case, induces a similar state of stress, one has an ideal situation in terms of structural performance. Between the two, however, even though shells have been enjoying widespread use in roofs all over the world since the 1920s, shells are relatively *newcomers* in the realm of *foundations* – starting out in the 1950s only – and used in instances which are few and far between. However, like in the superstructure, they have a forerunner in the form of *brick arches inverted* and used in foundations, in some parts of the world, including India, from very early times.

The twin attributes of a shell which recommends its use in roof are *economy* and *aesthetics*. Since the aspect of aesthetics is of no concern in the case of a buried structure like the foundation, it is the aspect of economy which alone holds the key to the acceptance and adoption of shells in foundations (Kurian, 2006). This factor is however held over for a more detailed presentation, in more analytical terms, later in this section.

16.3 Geometrical forms of shells used in foundations

Our exposition of this subject in this Module is essentially confined to the *geometrical aspect* of shells which are potentially suited for use in foundations, besides a few aspects such as comparative cost, stated above, besides construction.

16.3.1 The cone

The frustum of an *upright cone* is perhaps the simplest form in which a shell can be put to use in foundations. While smaller shells of this type can serve as *footings* for columns – preferably circular columns (Fig.16.1) – large shells can serve as *rafts* for tower-shaped structures such as chimney shafts (Fig.16.2). A major limitation of an *axisymmetric* shells such as the cone, arising out of its circular plan, is that its use is limited to *individual* units, unlike the hypar shell (*Sec.16.3.3*) which lends itself to combinations. It may be pointed out at this stage that, conical shell foundations of this type are basically different from the use of this shell as a substructure linking a superstructure, such as a television tower, supported on an annular raft at the bottom (see Fig.16.5).

A cone in the *inverted* position can also serve as the foundation for a guyed mast (Fig.16.3), or a cylindrical tank (Fig.16.4). The *frustum of an inverted cone* can also substitute for an annular raft under a conical substructure (Fig.16.5).

16.3.2 The spherical sector

The sector of a *spherical dome* in the *inverted* position can serve as a raft for cylindrical structures, or overhead structures supported on a circular row of columns, the latter resting on a circular *ring beam* at the top (Fig.16.6).

The above form is feasible when the area of support, dictated by soil conditions, does not exceed the plan area of the superstructure. Under stronger soil conditions, and the correspondingly reduced area requirement, the above shell can be deployed in an *annular* form (Fig.16.7). However, when the area requirement exceeds the plan area of the structure, the area of the foundation can be increased by the requisite amount by combining the *spherical sector* forming the inner unit with an outer unit in the form of the frustum of an *upright cone* (Fig.16.8). The inner shell of the *combined shell foundations* of this type can also be in an *annular form* (Fig.16.9). The case illustrated in Fig.16.10 is such a combination with the frustum of an *inverted cone* in the *inner* unit and the frustum of an *upright cone* in the *outer*, resulting in a *double cone folded shell.* A shell raft of this type can replace plain annular rafts to great structural advantage.

16.3.3 The hyperbolic paraboloid

Among the shells which have come into wider use in foundations, the *hyperbolic paraboloid* (or '*hypar*' or *h.p*. in short) has been the foremost thanks to its versatility which enables it to be deployed in *individual footings* – square or rectangular, with the column placed centrally or with single or double eccentricity – *combined* footings and *rafts*.

The hyperbolic paraboloidal shell is generated by moving a convex parabola over a concave parabola, or vice versa, at right angles to each other, which produces a *doubly-curved* shell, with curvatures in opposite directions (Fig.16.11). Horizontal planes intersect this surface along hyperbolae and hence the name 'hyperbolic paraboloid'. What is however striking is the fact that such a shell which sounds amazingly complex, both in name and geometry, is at the same time a very *simple* shape, when it is realised that, along the directions inclined at 45^0 to the directions of the above (principal) parabola, the surface consists of *straight lines*, at varying inclinations – called the straight-line generators of the shell – which make it a 'doubly ruled' surface. (The the above features can be identified from Fig.16.12, which is the central portion of a hyperbolic paraboloid bounded by straight line generators cut from the hyperbolic paraboloidal shell bounded by parabola given in Fig.16.11.) The latter is the most striking *geometrical property* of the shell, at any rate from the construction point of view, which is effectively exploited in profiling the soil, making the reinforcement grill and casting and finishing the shell in the case of the foundation. It has been said of this shell that it is 'structurally as efficient as it is geometrically elegant' (Kurian, 2006).

The hyperbolic paraboloid had been an early favourite in roofs where segments of this shell were joined in bewildering combinations producing panoramic roof profiles with high aesthetic appeal. One such form was the *inverted umbrella roof* supported on a single central column (Fig.16.13). It was eventually realised that this form could be inverted and used as footings for columns (Fig.16.14). Since these footings are the result of inverting the inverted umbrella roof, they have acquired the popular name *umbrella footings.* Such a shell footing is made up of four quadrants of the h.p. shell (of the type shown bold in Fig.16.12) joined together by a system of *edge* and *ridge beams*, the latter terminating at the *column base* (see Fig.16.14). Figs.16.15 and 16.16 show how such individual units are combined to form *combined footings* and *rafts*, respectively.

The h.p. shell, whether in roof or foundation, owes much of its popularity to the pioneering efforts of the renowned Mexican Engineer-Architect Felix Candela, who is also regarded as the father of modern shell foundations.

Kurian (2013: Sec.2.3.3) presents an overview of 'membrane analysis', 'bending analysis' and 'ultimate strength analysis' of all the above foundation shells, followed by their *design*.

16.4 Cost analysis

It has been possible to develop *expressions* for the *ratio of cost* between shell footings and plain footings, both designed for the *same column* load *P*, and the same *soil pressure p* – in other words, having the same plan dimensions. This has been possible by deriving expressions for the quantities of concrete and steel in either case as functions of *P* and *p* and applying the *ratio of unit cost r*, between steel and concrete, both placed in position, including labour. These results in respect of the conical and hypar footings are given in Figs.16.17 and 16.18 respectively. (For the same results pertaining to the spherical raft see Kurian, 2006:Sec. 6.8.3.) They all reveal that the economy with the shell *increases* with *increasing column load* and *decreasing soil pressure*, the latter applying to weaker soils. Among the three shells, the most favourable results are indicated in respect of the spherical shell, the ‘double compression’ in the shell explaining the same. The *ratio of weights* between the shell and plain footing alternatives is, however, almost entirely in favour of the shell. As regards the *cost ratio*, the crucial factor in the analysis is the unit cost ratio *r* between steel and concrete, which is both *country* and *time-specific*. This means, the picture of relative economy can vary either way, from country to country, and from one point of time to another.

It should be emphasised at this stage that the fact that shell foundations are cheaper on weaker soils (lesser values for *p*) does not imply that the same constitutes a geotechnical solution for weak soils. It only means that a shell footing, which is only a *structural alternative* to a plain footing, can be economical under certain conditions in terms of loads and soil reactions. By the same token one should also note that a shell foundation, which is a shallow foundation, is not meant to replace a deep foundation where soil conditions strictly point to the need for the latter.

16.5 Construction of shell foundations

Shell foundations can be constructed *in-situ* or *precast*. In the in-situ method, the *core soil,* which is the prism of soil underneath the shell lying in contact with the curved shell surface, whether it is the *natural* soil at site or *imported* from elsewhere for this purpose, can be profiled by rotating a template about a central vertical post, in the case of axisymmetric shells, and by moving a straight edge in the case of a ruled surface such as the hypar shell. Details on these procedures can be found in Kurian (2006: Sec.7.2).

16.5.1 Precast construction

While shell foundations have been cast *in-situ* in the majority of instances, the advantages of the shell, in terms of its lightness and consequent transportability are best exploited in *precasting*. Such precast shell footings can be cast in inverted concrete and wooden moulds. Whether the construction is in-situ or precast, it is important to ensure that there is *perfect contact* between the footing and the core soil at all points on the footing-soil interface. In precast construction it will not be expedient to cut the soil to the required profile and then install the footing, because in doing so, perfect footing-soil contact cannot be ensured under all circumstances. Instead, the footings are installed in trenches cut to level bottom. After centering and levelling, the core soil is prepared by pouring dry sand into the space below through a hole provided in the column base at the time of casting (see Fig.16.19). This sand is compacted by a *remote technique* called *centrifugal blast compaction* developed by the author at IIT Madras (1974) which carries out the process of compaction with great speed and efficiency. Fig.16.19 gives a schematic of the process, while Fig.16.20 shows a precast hypar footing installed in this manner and connected to a steel column.

There is indeed a strong case for establishing a *precasting industry*, utilising an integrated approach to all aspects pertaining to the computerised design, casting, curing, storage, transportation and installation of such footings. Kurian (2006: Sec.7.7) throws much light on the scope of such a venture.

16.5.2 The technique of remote compaction

The *centrifugal blast compaction* mentioned above, is effected by means of a simple equipment called a *centrifugal vane rotor* which consists of a rotating spindle carrying falling vanes or blades, designed as a simple *attachment* to an ordinary *needle vibrator* used for compacting fresh concrete (Fig.16.21).

In the technique, after pouring a batch of dry sand, the rotor is inserted into the hollow space below through the hole in the column base (Fig.16.19). When the motor is now switched on, the vanes open out automatically due to the centrifugal action and start rotating at high speeds. This high speed rotation of the vanes creates a *heavy blast* in the hollow space, under the influence of which, the sand particles become quickly *air-borne* and start moving radially outwards with *high velocities*. These particles *collide* against the inner surfaces of the shell footing and settle down to positions of *maximum density*. The succeeding particles one after another are automatically forced to occupy positions leaving the least of voids, thereby giving rise to *maximum compaction*. As this process continues, the entire space gets progressively filled up from the periphery inwards. (Fig.16.22 shows two successive stages of infilling and compaction underneath a hypar footing installed by this method.) The work can be stopped on reaching the central portion which is directly accessible for manual compaction through the hole.

The technique has been found to be *highly satisfactory* in terms of facility of work, speed, degree of compaction and overall efficiency.

16.6 Case histories

Kurian (2006: Sec.7.9) presents some *important case histories*, drawn from various parts of the world, on the use of shell foundations of different types, starting with the hypar footings poured by Candela in 1953 for the Mexico City Customs House. Another topic he has touched upon is the use of shells in anchors (Kurian, 2013: Sec. 2.3.6).

Conclusion

For a detailed treatment of the subject of shell foundations, which also includes their *geotechnical* performance in terms of bearing capacity and settlement, the reader is advised to consult the author's treatise on the subject (Kurian, 2006) which comprehensively covers all aspects pertaining to the *geometry, analysis, design* and *construction* of shell foundations.